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INT CL⁵ G01S

(54) **Radio frequency ranging apparatus**

(57) A transmitter generates a pseudorandom noise (PN) code (10) and modulates (20) a carrier. A receiver correlates the received PN code with a reference. The PN code generator generates a plurality of PN codes having the same number of chips and a common chip rate, but equally time shifted from one another within the period of a single chip of the PN codes. The modulator modulates a corresponding plurality of carriers (which may be the same) with respective codes for transmission. The receiver combines the received PN codes to recover a high rate PN code having a chip rate which is the product of the common chip rate and the number of the received PN codes. The correlator correlates the recovered higher rate PN code with a similar reference PN code.

Application is to path-difference or radar systems.

FIG. 1.

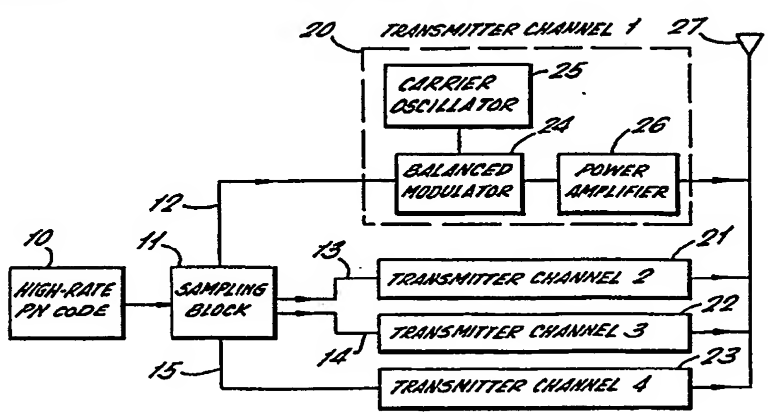
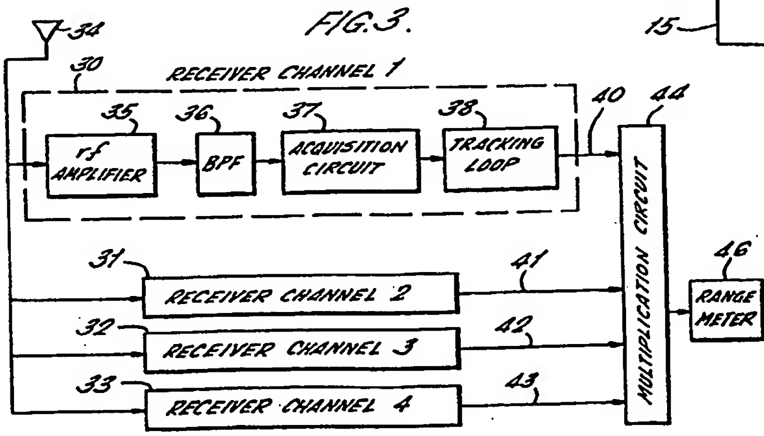


FIG. 3.



At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

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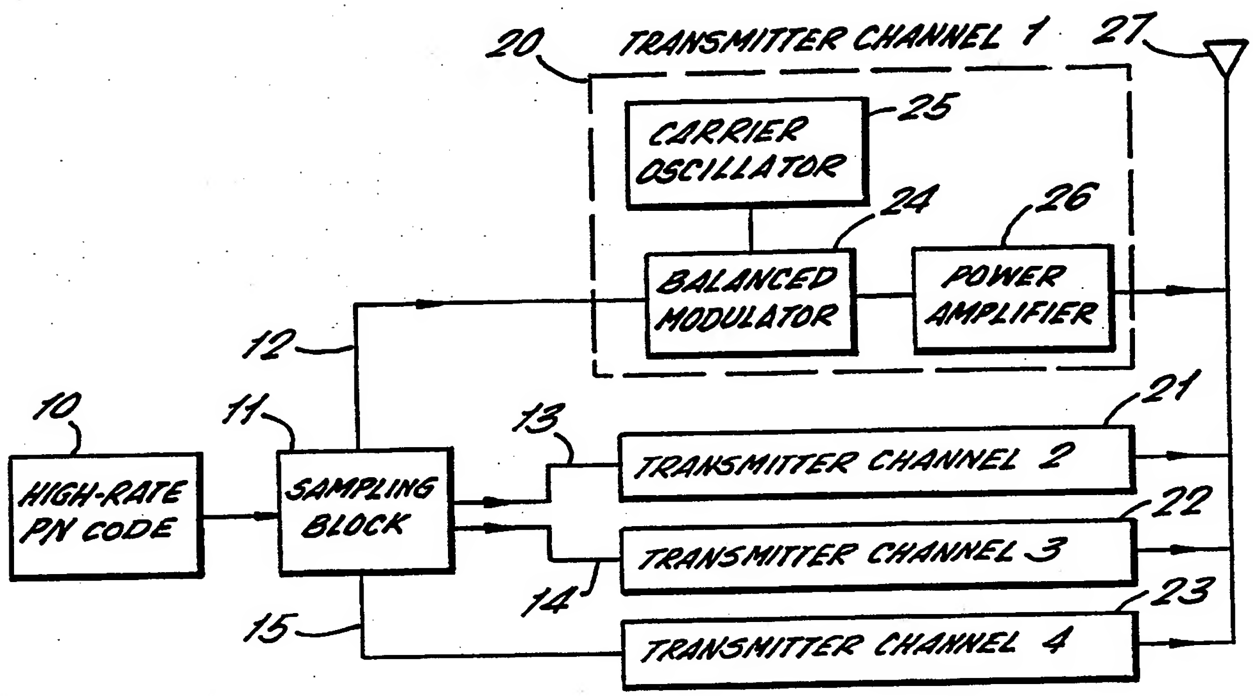
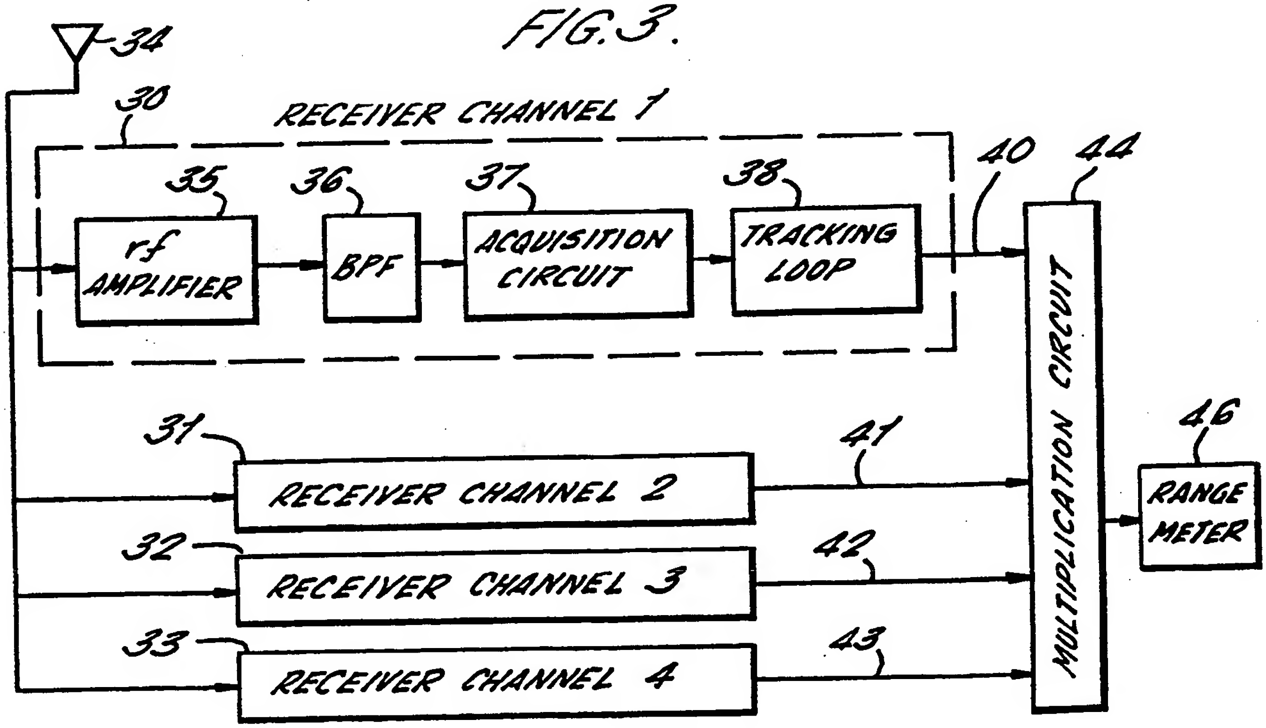
FIG. 1.



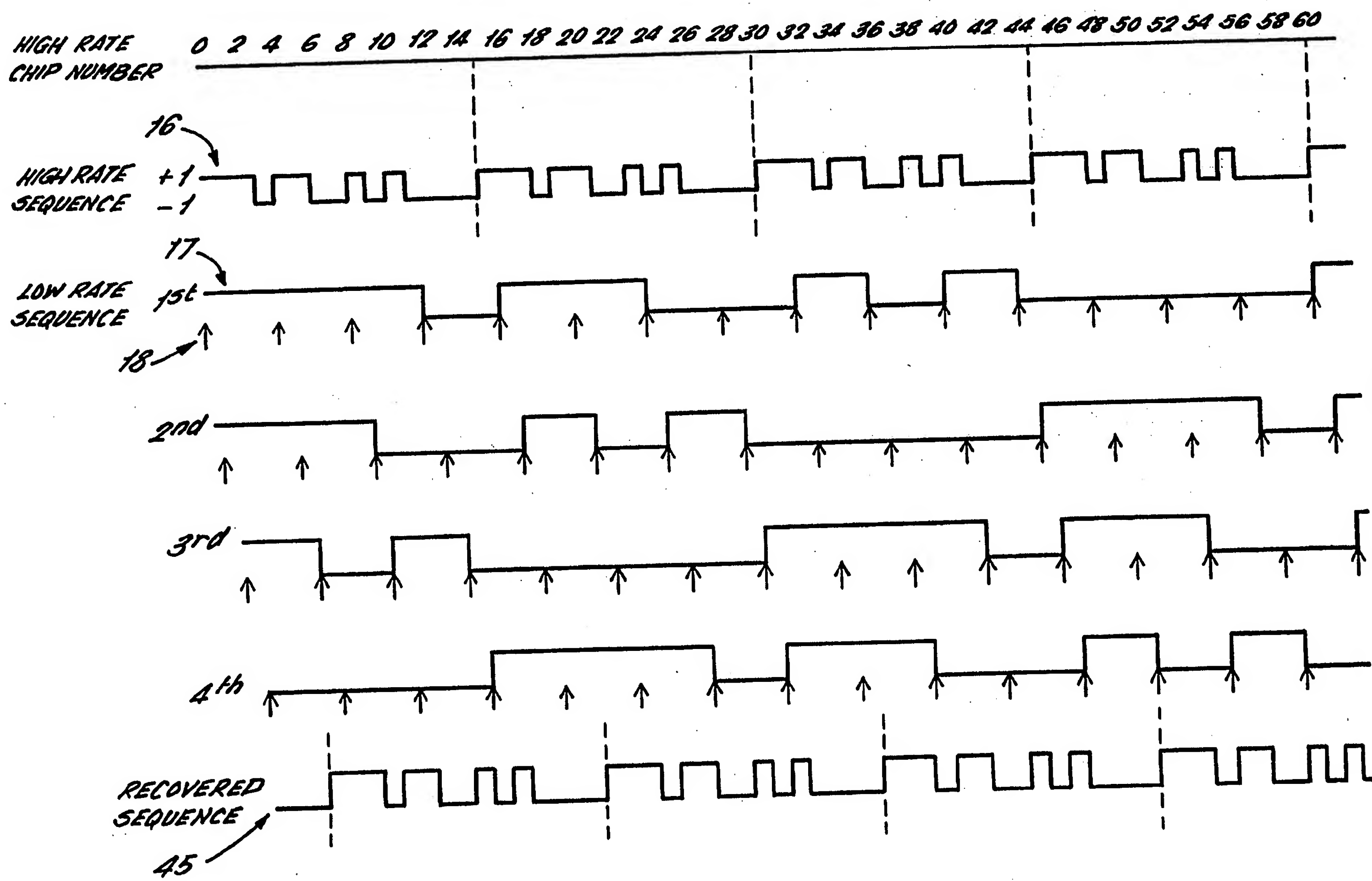
TRANSMITTER CHANNEL 1
20
27
CARRIER OSCILLATOR
25
24
26
BALANCED MODULATOR
POWER AMPLIFIER
12
10
11
13
21
HIGH-RATE PN CODE
SAMPLING BLOCK
TRANSMITTER CHANNEL 2
22
TRANSMITTER CHANNEL 3
14
23
15
TRANSMITTER CHANNEL 4

FIG. 3.



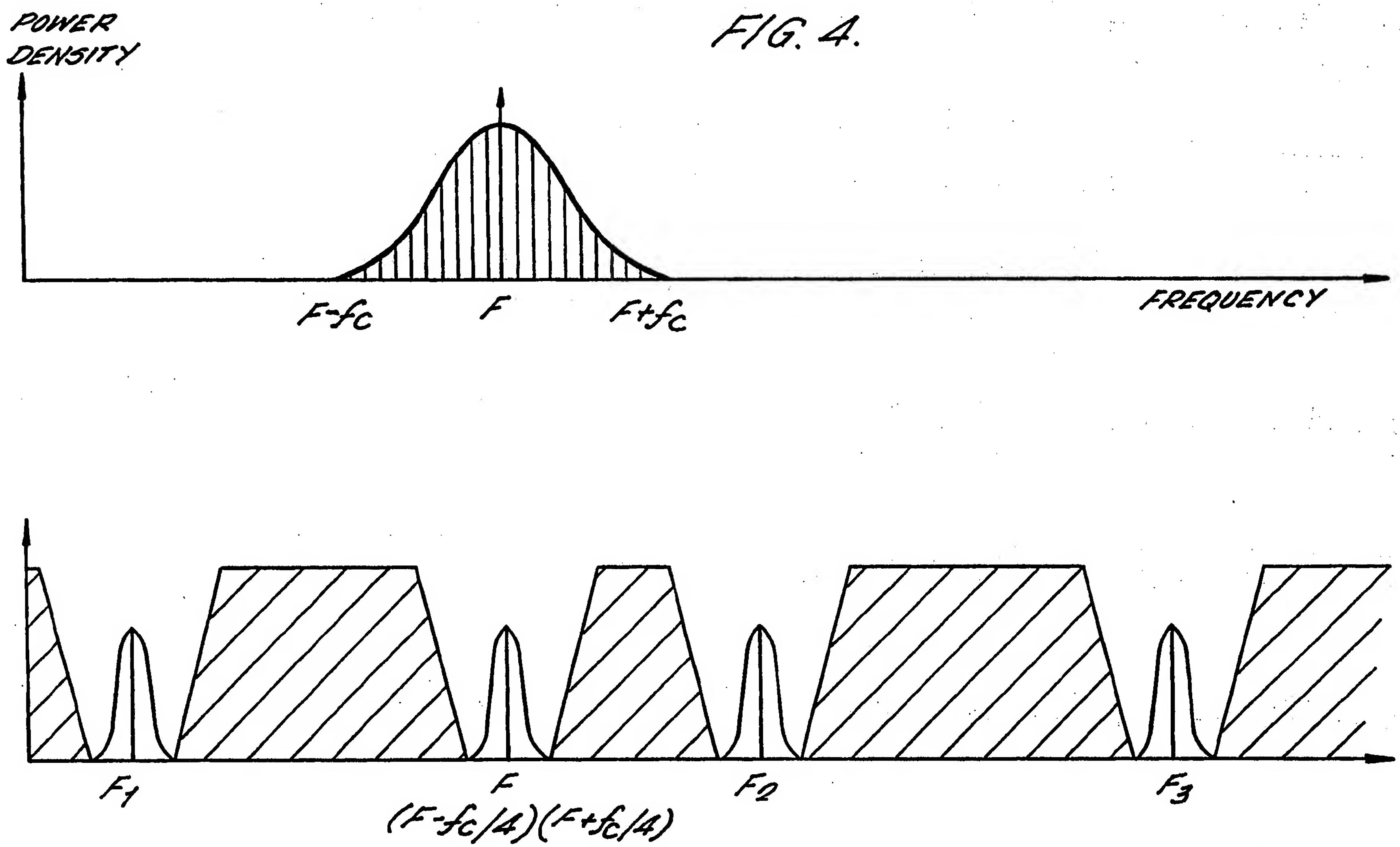
34
30
RECEIVER CHANNEL 1
40
44
35
36
37
38
rf AMPLIFIER
BPF
ACQUISITION CIRCUIT
TRACKING LOOP
MULTIPLICATION CIRCUIT
31
41
46
RECEIVER CHANNEL 2
RANGE METER
32
42
RECEIVER CHANNEL 3
33
43
RECEIVER CHANNEL 4

FIG. 2.

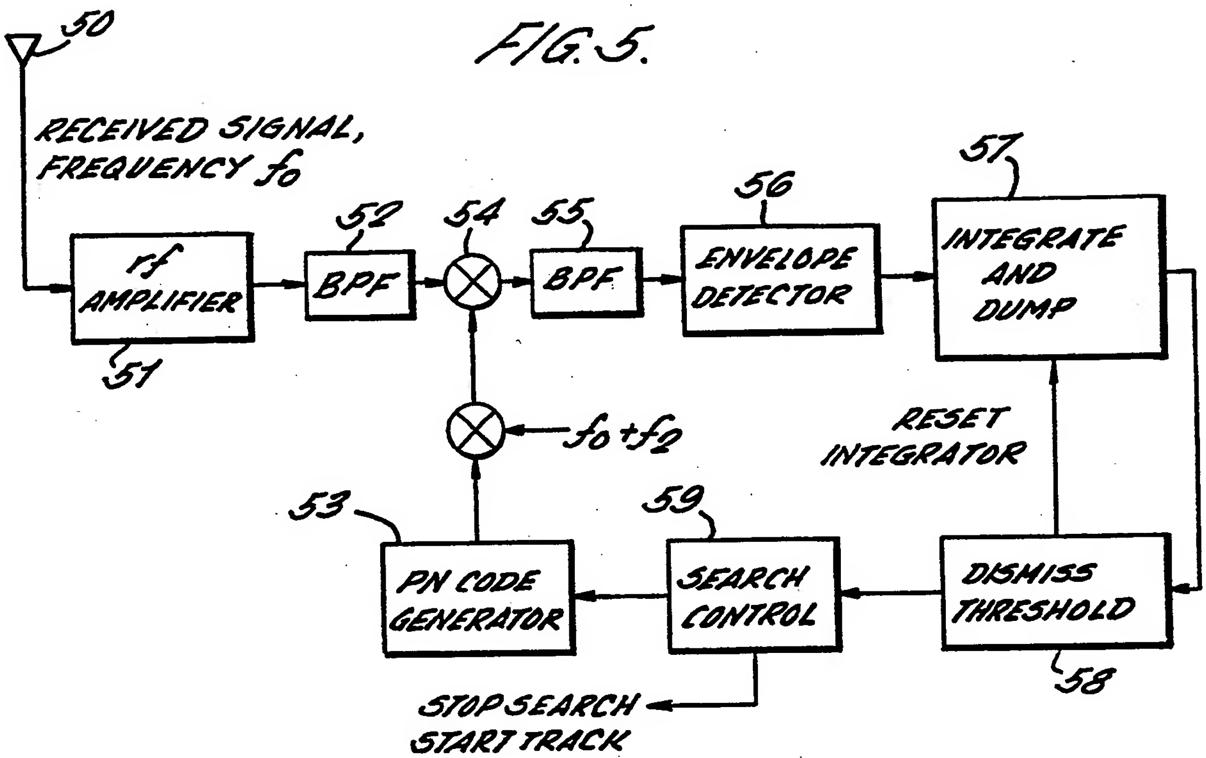


HIGH RATE CHIP NUMBER
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60
16
HIGH RATE SEQUENCE
+1
−1
17
LOW RATE SEQUENCE
1st
18
2nd
3rd
4th
RECOVERED SEQUENCE
45

FIG. 4.

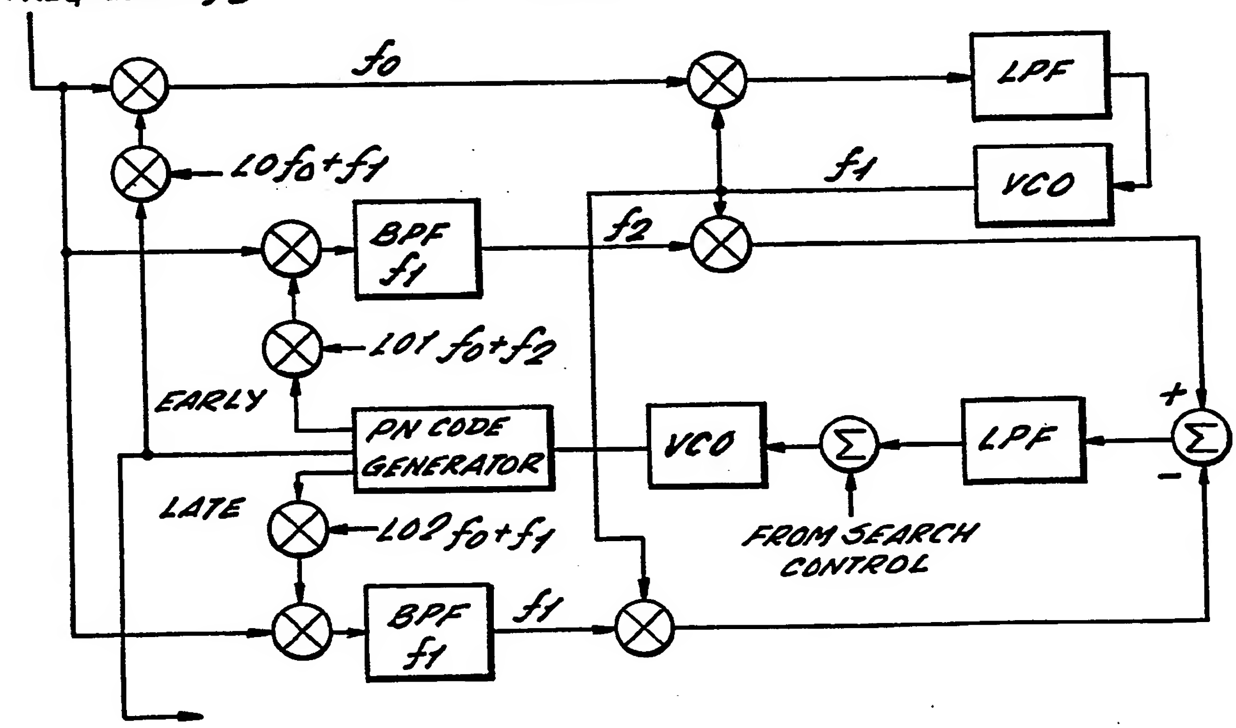


4/8



50
RECEIVED SIGNAL, FREQUENCY f_0
57
56
52
54
55
rf AMPLIFIER
BPF
BPF
ENVELOPE DETECTOR
INTEGRATE AND DUMP
51
f_0+f_2
RESET INTEGRATOR
53
59
PN CODE GENERATOR
SEARCH CONTROL
DISMISS THRESHOLD
58
STOP SEARCH START TRACK

FIG. 5.



RECEIVED SIGNAL, FREQUENCY f_0
f_0
LPF
LO f_0+f_1
f_1
VCO
BPF f_1
f_2
LO1 f_0+f_2
EARLY
PN CODE GENERATOR
VCO
LPF
+
−
LATE
LO2 f_0+f_1
FROM SEARCH CONTROL
BPF f_1
f_1

FIG. 6.

FIG. 7.

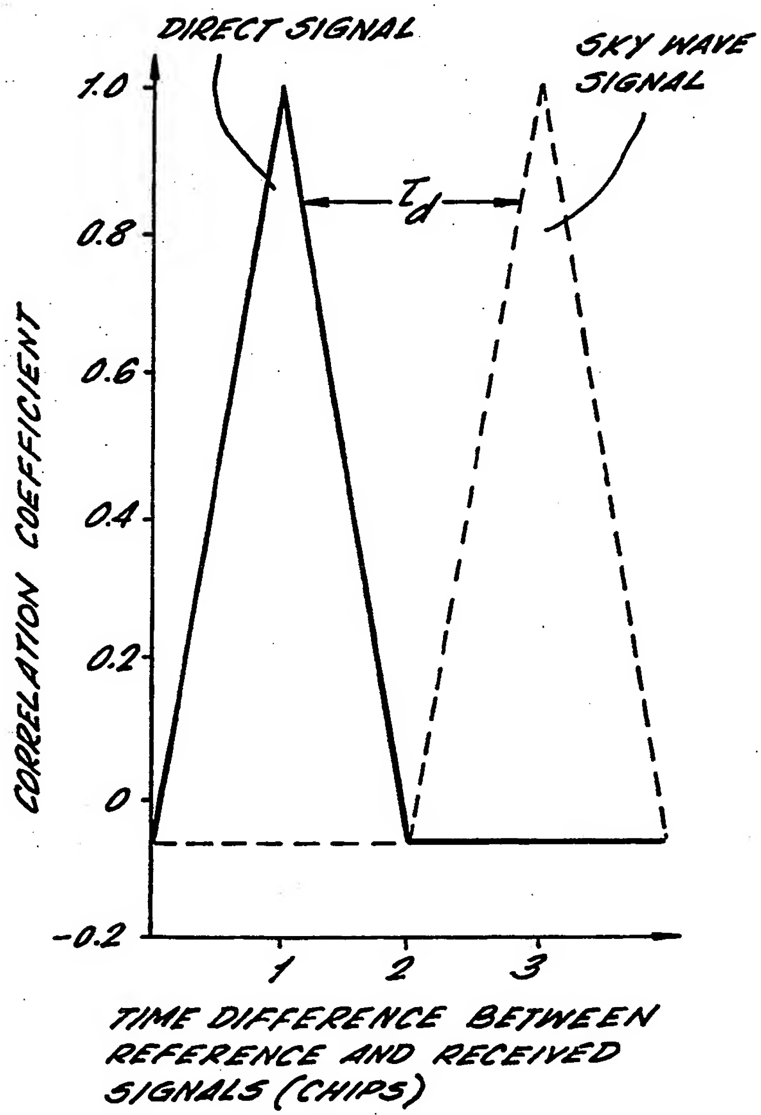
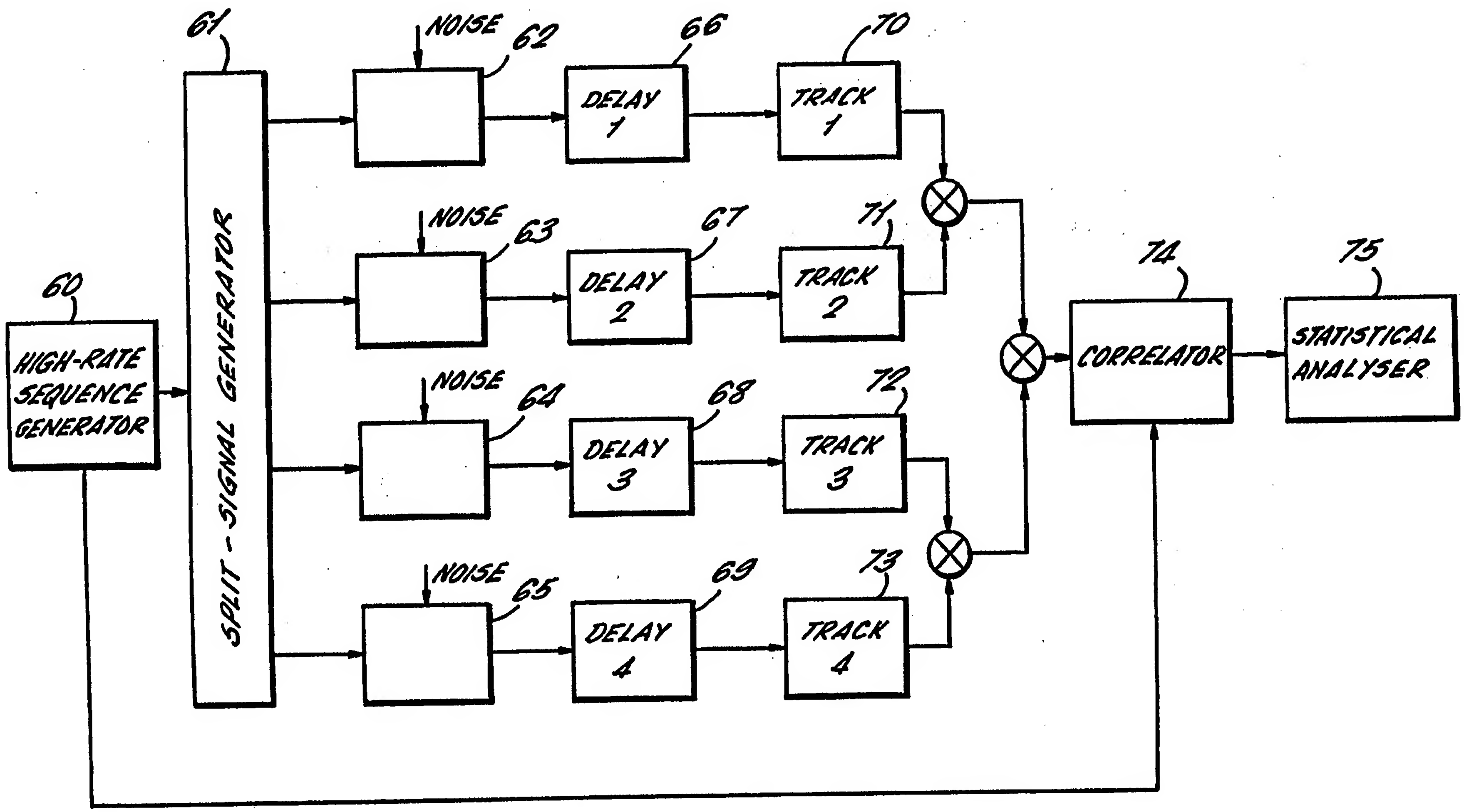

DIRECT SIGNAL
SKY WAVE SIGNAL
τ_d
1.0
0.8
0.6
0.4
0.2
0
-0.2
CORRELATION COEFFICIENT
1
2
3
TIME DIFFERENCE BETWEEN REFERENCE AND RECEIVED SIGNALS (CHIPS)

FIG. 8.



HIGH-RATE SEQUENCE GENERATOR
60
SPLIT - SIGNAL GENERATOR
61
NOISE
62
NOISE
63
NOISE
64
NOISE
65
DELAY 1
66
DELAY 2
67
DELAY 3
68
DELAY 4
69
TRACK 1
70
TRACK 2
71
TRACK 3
72
TRACK 4
73
CORRELATOR
74
STATISTICAL ANALYSER
75

FIG. 9.

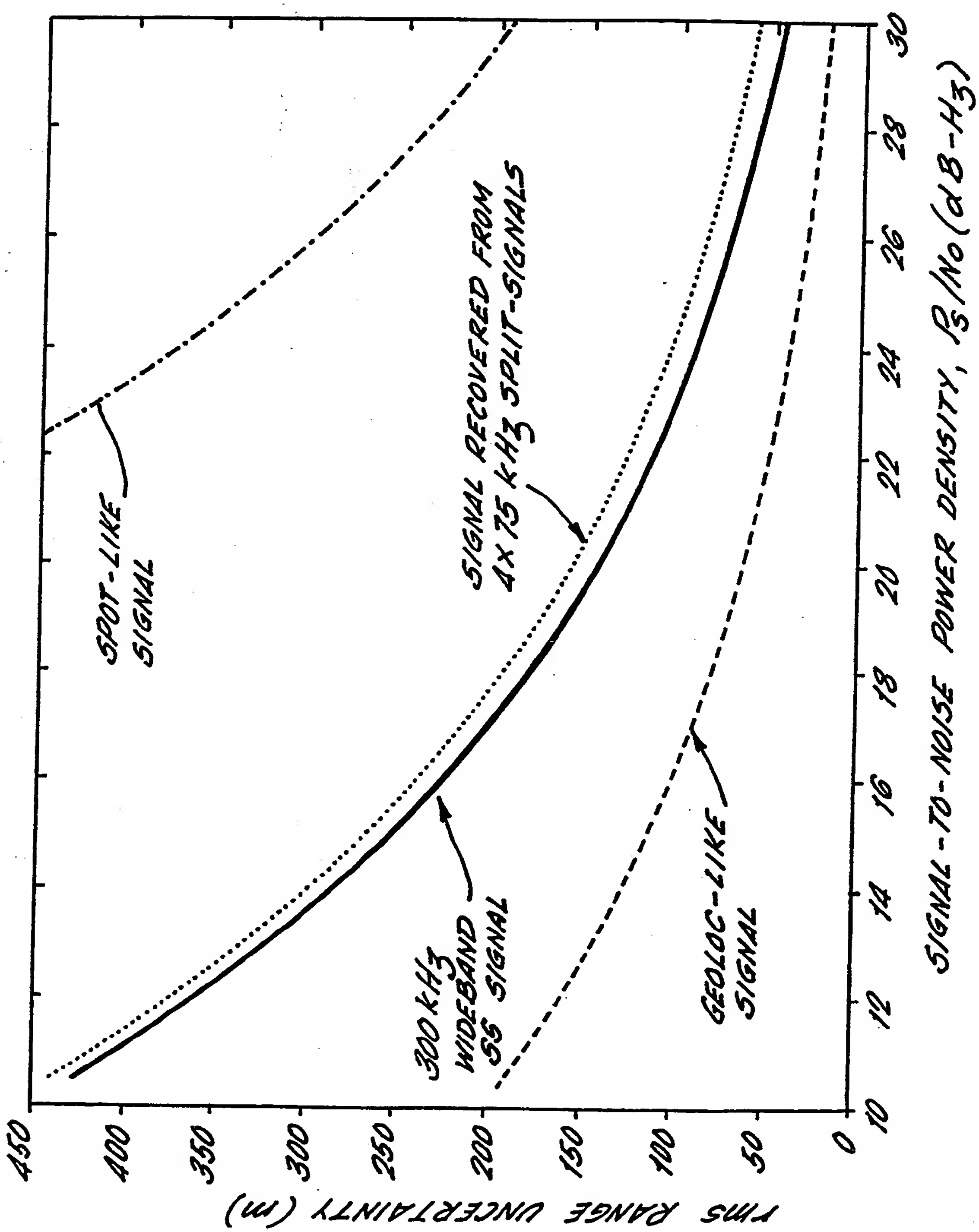
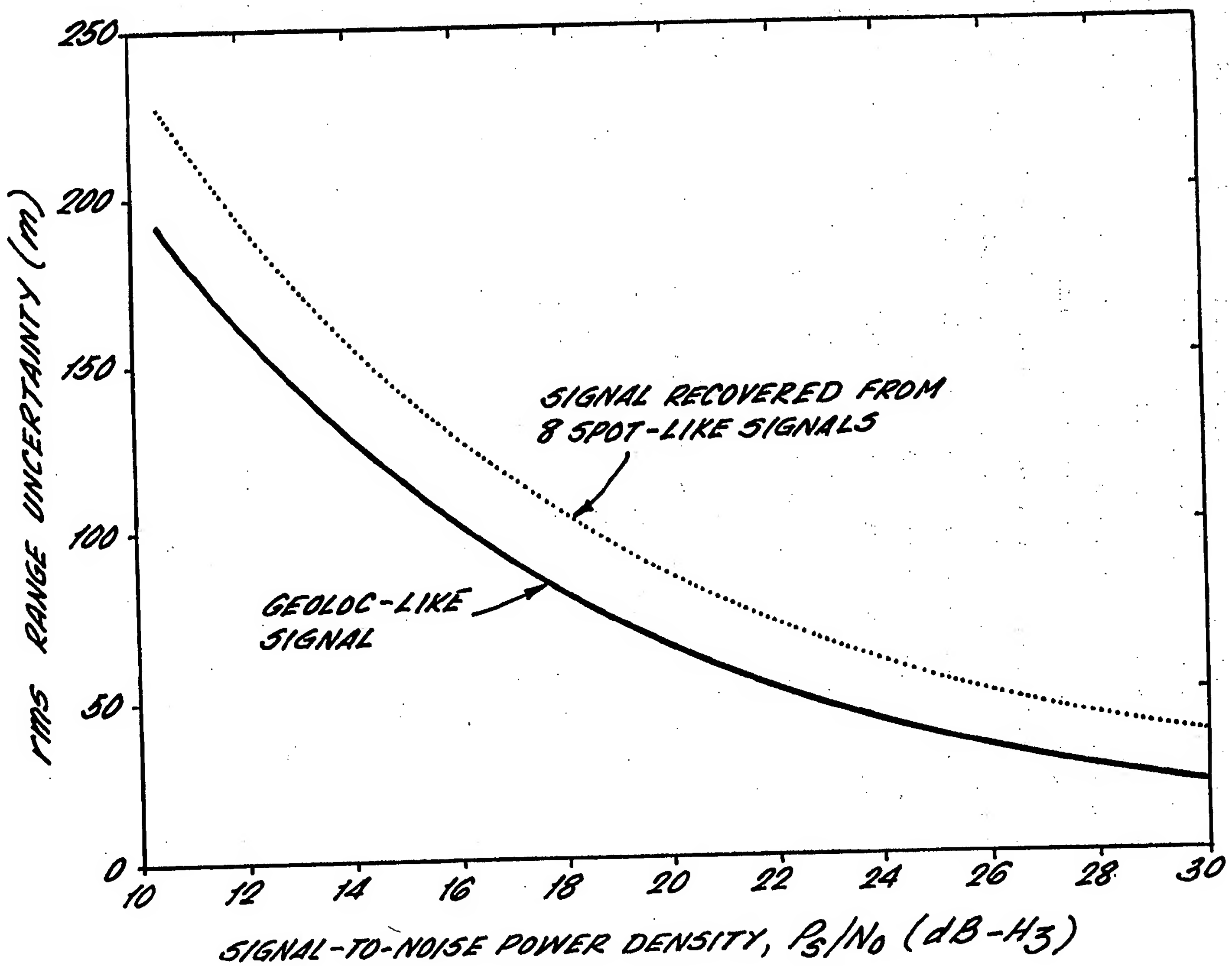

SPOT-LIKE SIGNAL
SIGNAL RECOVERED FROM 4X75 kHz SPLIT-SIGNALS
300 kHz WIDEBAND SS SIGNAL
GEOLOC-LIKE SIGNAL
rms RANGE UNCERTAINTY (m)
0
50
100
150
200
250
300
350
400
450
SIGNAL-TO-NOISE POWER DENSITY, Ps/No (dB-Hz)
10
12
14
16
18
20
22
24
26
28
30

FIG. 10.



250
200
150
100
50
0
10
12
14
16
18
20
22
24
26
28
30
rms RANGE UNCERTAINTY (m)
SIGNAL-TO-NOISE POWER DENSITY, P_S/N_0 (dB-Hz)
SIGNAL RECOVERED FROM
8 SPOT-LIKE SIGNALS
GEOLOC-LIKE
SIGNAL

RADIO FREQUENCY RANGING APPARATUS

The present invention concerns radio frequency ranging apparatus. The invention is particularly applicable to radio frequency ranging apparatus used as radio positioning apparatus, e.g. as a navigational aid. However, the invention also has application in other forms of ranging apparatus, such as radar, in which the propagation time of radio signals is used to obtain a range and/or a position. In radio positioning systems, the position of a receiver relative to a number of transmitters is determined. In radar systems, the positions of the transmitter and receiver are generally known (usually the same) and the radio signal propagation time is employed to determine the range of a reflecting target.

In radio positioning systems, spread-spectrum (SS) are known and used particularly to reduce interference between the transmitters of the radio positioning system and other users of the radio frequency spectrum. Spread-spectrum techniques permit the power spectral density (psd) to be kept low whilst maintaining sufficient total power in the transmitted signal for adequate reception.

In some systems, such as radar, the radio signals can be transmitted as short pulses of radio frequency energy, but this is an inefficient method of ensuring adequate mean power, and also generates high levels of interference. For radio positioning systems, a commonly employed technique is to measure the phase on reception of unmodulated continuous wave (CW) narrow band carrier. Systems employing this technique include the navigation systems called Omega and Hyper-Fix. A problem with CW systems is that a receiver cannot distinguish between

multiples of 2π in phase. In addition, the use of CW does not permit discrimination between the wanted signal propagated via the direct path between transmitter and receiver, and interference propagated by other paths, such as the so called "sky wave" signal reflected by the ionosphere.

More recently, spread-spectrum techniques have been introduced for radio positioning and current examples include Geoloc, Syledis and Spot. In spread-spectrum techniques for radio positioning employed hitherto, a carrier wave is phase angle modulated by a digital code sequence. The digital code sequence is typically a pseudorandom noise (PN) code. In a PN code, the individual elements of the binary code sequence are known as chips, and the frequency of these code elements is known as the chip rate. A particular PN code has a predetermined number of chips before the code sequence repeats and this represents the length of the code.

The presence of a defined time structure in the transmitted signal, as determined by the chip rate, permits acute time resolution of signals at a receiver. On the other hand, the PN code can have a substantial length before repeating, determined by the number of chips in the code sequence, so that range ambiguities can be avoided.

Importantly also, modulation of a carrier frequency with a PN code distributes the transmitted power over a band effectively corresponding to approximately twice the chip rate, so that power spectral density within the band can be reduced.

Nevertheless, with radio positioning systems uitilising SS techniques, problems still remain of interference with other users of the available spectrum. Various techniques have been proposed of shaping the transmitted spectrum of the SS signal but none have proved

particularly effective or else involve substantial loss of performance.

According to the present invention, radio frequency ranging apparatus comprises a transmitter having a pseudorandom noise (PN) code generator and a modulator to modulate a carrier frequency with the generated PN code for transmission; and a receiver comprising processing means incorporating a correlator to correlate a PN code, recovered from a radio signal received from the transmitter, with a similar reference PN code and providing a time signal dependent on propagation time for said radio signal between the transmitter and the receiver, wherein said PN code generator is arranged to generate a plurality of PN codes having the same number of chips and a common chip rate, said PN codes being equally time shifted one from the next within the period of a single chip of said PN codes, and said modulator is arranged to modulate a corresponding plurality of carrier signals with respective said codes for transmission as respective radio signals, and wherein the receiver is arranged to receive said respective radio signals and said processing means includes combining means to combine the received PN codes to recover a higher rate PN code having a chip rate which is the product of said common chip rate and the number of said received PN codes, said correlator being arranged to correlate said recovered higher rate PN code with a similar reference PN code.

With the apparatus of the present invention, instead of transmitting a single carrier with a relatively high chip rate PN code, the transmitter is arranged to transmit several different carriers each modulated with a respective lower rate PN code. The different lower rate codes are all time shifted relative to one another by an equal fraction of one lower rate code period corresponding to the number of codes and carriers. On reception, a

higher rate PN code is recreated by combining the received lower rate codes. It has been shown that the recombined higher rate code provides substantially as good time correlation performance for signal to noise ratio in the received signals, as would be provided by a single carrier modulated with the higher rate PN code.

One advantage of the apparatus proposed above is that each of the individual carrier signals can have a different frequency and can be located as desired in the available frequency spectrum, so as to produce minimum interference with other users. Thus, for example, instead of transmitting a single carrier with a band width of say eight units, with the above described apparatus eight carriers may be transmitted each with a band width of a single unit and these eight carriers may be located in the spectrum as desired. It can be shown that the performance of the resulting apparatus is scarcely impaired.

In particular, the individual carriers may be located in available gaps of the spectrum. The apparatus is suitable for use in a frequency band in which multiple spectral gaps are normally available but where there is no continuously available gap adequate for the wide band SS signal. Further, the apparatus may be modified to take advantage of relatively narrow gaps available in the spectrum for short periods of time. To this end, the apparatus may include monitoring apparatus for monitoring when gaps in a predetermined spectral region become available and a control apparatus for controlling the transmitter to generate carrier frequencies for transmission in these gaps. The receivers may then include seeker means for seeking the transmitted carrier frequencies for reception.

In an alternative arrangement, each carrier signal modulated by a lower rate PN code can have the same frequency or different frequencies where the band widths

of each carrier frequency overlaps. This is possible since where four lower rate PN codes are used, only one quarter of the available bandwidth is used. Each of the PN codes are orthogonal and uncorrelated in time. Two lower rate PN codes are identical except for a time shift of one quarter of the lower rate chip period. In this arrangement the receiver exploits the orthogonality property to identify uniquely each lower rate PN code modulated carrier signal. When one lower rate PN code modulated carrier signal is being received the receiver is locked onto and tracking the desired signal. The other signals are all orthogonal to the desired signal and the interference power contributed to these other signals is sufficiently small that it can be neglected. It is of the order of 1/L for each unwanted carrier signal and under normal operating conditions will be significantly less than the receivers thermal noise component and can thus be neglected. This property is exploited by communication systems and is commonly called code-division-multiple-access (CDMA). This property has also been exploited in navigation systems such as the American military satellite navigation system GPS.

One drawback with using the orthogonality of the lower rate PN codes and using a single carrier frequency or overlapping carrier frequency bands is that the power spectral density presented to other uses of the same radio band is increased. There is however a reduction in the required bandwidth for the radio frequency ranging apparatus compared to the use of separate carrier frequencies.

An additional advantage in using a single carrier frequency is that there is no difference in propagation delay for the carrier signals as can occur when the lower rate PN codes modulate different frequencies.

Conveniently, said PN code generator in the transmitter comprises means to generate a PN code having a higher chip rate and sampling means to sample the chips of said higher rate PN code sequentially to form said plurality of PN codes at a common lower chip rate which is equal to said higher rate divided by the number of said plurality of PN codes. The higher rate code may then correspond to the recovered higher rate code at the receiver. Alternatively, however, multiple lower rate PN codes may be generated independently with the required time spacing. Where the lower rate codes are generated by sampling a single higher rate code, the lower rate codes will normally have the same length (at the lower rate) as the original higher rate code, and will all in fact comprise the same code sequence but at different times in the sequence, provided that the number of lower rate codes is an integer power of two and relatively prime in number to the number of shift register stages (or code length) of the higher chip rate code. Where the lower rate codes are generated independently, the lower rate codes will be related to each other by time shifts and will also comprise the same code sequence but at different times in the sequence provided that the number of lower rate codes is an integer power of two and relatively prime in number to the code length of the higher chip rate sequence. This may be especially useful in radio positioning systems where the different carrier signals from a single transmitter of the system will be modulated with the same PN code for identification purposes.

In the receiver, said combining means may comprise adding means for performing modulo two addition of the received PN codes if they are (0,1). Alternatively, if the chips of the PN codes are represented as +1 and -1 in accordance with their binary state, the combining means may comprise multiplying means to multiply together the

chips of the received PN codes. These two alternatives represent coherent receivers where the receiver reference signals have exactly the same frequency and phase as the incoming signals and signal processing may be done directly on the PN codes at baseband. This is the ideal situation but in practice because of problems such as propagation path effects, receiver oscillator instabilities etc., the reference signals are not of exactly the same frequency and phase. Thus a non coherent receiver must be employed as standardly used in SS sytems. In one such system the high rate clock correction is recovered by adding error voltages of low rate delay lock loops.

As contemplated above, the radio frequency ranging apparatus may be configured as radio positioning apparatus, wherein the apparatus includes at least three said transmitters, and at least one said receiver, said processing means thereof providing said time signals for each of the transmitters from which radio signals are received at the receiver and identifying a position for the receiver relative to the transmitters from said time signals. The transmitters may have respective different carrier frequencies or sets of carrier frequencies. Alteratively, in a time domain multiple access system (TDMA) the transmitters use the same carrier frequencies or sets of carrier frequencies and are assigned time slots for transmission.

Where the carrier frequencies used by the or each transmitter can vary, making use of gaps available in the spectrum for limited periods of time, provision may be made for encoding the transmitted carriers with frequency information identifying the transmitted carrier frequencies. Then such information can be decoded at a receiver to assist in locating all the carrier frequencies of a set for a particular transmitter.

It will be appreciated that the present invention also provides a transmitter for use in radio frequency ranging apparatus as described above and comprises a pseudorandom noise (PN) code generator and a modulator to modulate a carrier frequency with the generated PN code for transmission, wherein said PN code generator is arranged to generate a plurality of PN codes having the same number of chips and a common chip rate, said PN codes being equally time shifted one from the next within the period of a single chip of said PN codes, and said modulator is arranged to modulate a corresponding plurality of carrier signals with respective said codes for transmission as respective radio signals.

The invention further provides a receiver for use in radio frequency ranging apparatus as described above which comprises processing means incorporating a correlator to correlate a received radio signal modulated with a PN code with a similar reference PN code and providing a time signal dependent on a propagation time for said radio signal between a transmitter and the receiver, wherein the receiver is arranged to receive a plurality of radio signals from a transmitter comprising respective carrier signals modulated by respective PN codes each having the same number of chips at a common chip rate, said PN codes being equally time shifted one from the next within the period of a single chip of said PN code, and the processing means includes combining means to combine the received PN codes to recover a higher rate PN code having a chip rate which is the product of said common chip rate and the number of said received PN codes, said correlator being arranged to correlate said recovered higher rate PN code with a similar reference PN code.

The present invention may also be regarded as a method of radio frequency ranging comprising the steps of generating a pseudorandom noise (PN) code, modulating a

carrier frequency with the generated code, transmitting the modulated carrier frequency, receiving the modulated carrier frequency signal at a receiver and processing the received signal by correlating a PN code recovered from the signal with a similar reference PN code and providing a time signal dependent on a propagation time for the radio signal between the transmitter and the receiver, wherein a plurality of PN codes are generated at the transmitter, the codes having the same number of chips and a common chip rate, and being equally offset in time one from the next within the period of a single chip of said PN code, and respective said codes are modulated on corresponding plurality of carrier signals which are then transmitted, and wherein the respective transmitted radio signals are received at a receiver and the received PN codes thereof are combined to recover a higher rate PN code having a chip rate which is the product of said common chip rate and the number of said received PN codes, said recovered higher PN code being then correlated with a similar reference PN code.

Examples of the present invention will now be described with reference to the accompanying drawings in which:

Figure 1 is a block schematic diagram illustrating a transmitter embodying features of the present invention;

Figure 2 is a timing diagram illustrating splitting a higher rate PN code sequence into four lower rate sequences;

Figure 3 is a block schematic diagram of a receiver embodying features of the present invention;

Figure 4 is a graphical representation of the distribution of power density with frequency of a higher rate PN coded radio signal, for comparison with four lower rate encoded radio signals at different carrier frequencies;

Figure 5 is a block diagram illustrating a signal acquisition system for a direct sequence spread-spectrum receiver;

Figure 6 is a block diagram illustrating a signal tracking loop for a coherent direct sequence spread-spectrum receiver;

Figure 7 is a graphical representation of the correlation coefficients of a DS-SS receiver illustrating the delayed reception of a sky wave signal;

Figure 8 is a block diagram illustrating a computer model used to simulate operation of the present invention;

Figure 9 is a graphical representation of range uncertainty versus signal-to-noise power density for different spread-spectrum systems and illustrating the performance of an example of the present invention; and

Figure 10 is a further graphical representation of range uncertainty versus signal-to-noise power density illustrating the performance of another example of the present invention.

Referring to Figure 1, a transmitter is illustrated which embodies features of the present invention and would be used in a radio positioning system. In a radio positioning system, a number of such transmitters will be provided to cover a geographical area in which radio positioning using the system is required. Generally, in radio positioning systems of this kind, a vehicle requiring to identify its position carries a suitable radio receiver for receiving signals transmitted by the system transmitters. Although the system is not normally capable of determining the propagation time itself from any one transmitter to the vehicle, having no reference time from which to work, the receiver can obtain values for the difference in propagation time of the signals from a pair of transmitters, using the signal

received from one transmitter as a timing reference for the other. A delay difference from the signals of a single pair of transmitters establishes a line-of-position (LOP), which is an hyperbolic curve on a map indicating the locus of possible positions for the receiver corresponding to the particular delay difference. By obtaining a second LOP from a further pair of transmitters (one of which may be a transmitter from the first pair), the position of the receiver is then represented by the intersection point of the two LOPS.

The transmitter illustrated in Figure 1, has a generator 10 for generating a first PN code at a relatively high rate, say 300 kHz. This high rate PN code sequence is fed to a sampling block 11 in which successive chips of the higher rate code are sampled onto four output lines 12, 13, 14 and 15, to produce four lower rate PN codes on these lines each having a chip rate which is a quarter of the rate of the high rate code from generator 10. This sampling procedure is best understood by referring to Figure 2 in which a simple fifteen chip PN sequence is used for purposes of illustration. The higher rate sequence is illustrated at 16 and as can be seen the sequence repeats every fifteen chips.

A first low rate sequence, 17 is produced by sampling every fourth chip of the higher rate sequence starting with chip 0 and continuing with chips 4, 8 etc. as shown by the arrows 18. The sampled level from the higher rate sequence is maintained in the low rate sequence until the next sample is taken to produce the lower rate chip sequence as illustrated at 17.

Second, third and fourth lower rate sequences are similarly obtained by sampling at the first, fifth, ninth etc. chips, the second, sixth, tenth etc. chips, and the third, seventh, eleventh etc. chips of the higher rate sequence.

Observing the form of the four low rate sequences produced as illustrated in Figure 2, it can be seen that these are in fact all fifteen chip sequences which correspond to the chips of the higher rate sequence but at one quarter of the rate. The four sequences are sequentially spaced in time one from the next by one quarter of a lower rate sequence period.

From the example mentioned above where the higher rate sequence is 300 kHz, each of the lower rate sequences has a chip rate of 75 kHz.

These four lower rate sequences are fed on lines 12, 13, 14 and 15 from the sampling block to respective transmitter channels 20, 21, 22 and 23 as illustrated in Figure 1. In each transmitter channel, the respective lower rate PN code is phase modulated by means of a balanced modulator 24 on a carrier signal from a carrier oscillator 25. The resulting modulated carrier radio frequency signal is then amplified in a power amplifier 26 for transmission from a common antenna 27.

The carrier oscillators 25 of the four transmitter channels 20, 21, 22 and 23 can be arranged to provide carrier frequencies which are sufficiently spaced in the radio spectrum so that the spectra of the modulated radio signals do not overlap. Alternatively, carrier frequencies which overlap, or a single carrier frequency can be used since the PN codes are orthogonal.

Referring now to Figure 3, for simplicity a coherent receiver is shown for receiving signals transmitted by a transmitter as shown in Figure 1. The receiver has a corresponding number of receiver channels, 30, 31, 32 and 33 receiving radio frequency signals from a common antenna 34. Each receiver channel includes an rf amplifier 35 feeding a band pass filter 36 which is tuned to pass a frequency band encompassing a selected one of the modulated carrier frequencies from the particular

transmitter to which the receiver is currently tuned.

The band pass filtered signal is then supplied to an acquisition circuit 37 which acquires an initial lock on the PN phase coded signal for use in controlling a subsequent tracking loop 38 which controls a locally generated lower rate PN code so as accurately to track the PN code modulated in the received signal. The output from the tracking loop 38 is a lower rate PN code having an unknown delay relative to the same code as transmitted from the antenna 27 of the transmitter. This delay is accurately dependent on the propagation time from the transmitter.

At the same time, receiver channels 31, 32 and 33 operate on the modulated carrier frequencies from transmitter channels 21, 22 and 23 of the transmitter and produce corresponding PN code sequences having approximately the same delay representing the propagation time from the transmitter. Ideally the delays for each carrier frequency (if different frequencies are used) are not the same and differential propagation effects will lead to discrepancies which can be compensated.

The four PN code sequences on lines 40, 41, 42 and 43 are supplied to a multiplication circuit 44 in which they are combined.

The multiplication circuit 44 combines the four lower rate PN code sequences derived from the four received rf signals to recover a higher rate sequence. In the present example, the recovered higher rate sequence corresponds to the original higher rate sequence from the generator 10 in the receiver.

If the binary states of the four lower rate code sequences are represented by +1 and -1, it can be seen that multiplication together of the states pertaining from time to time for the four lower rate sequences reproduces the higher rate sequence. Considering again Figure 2, the

recovered higher rate sequence is shown at 45 and it will be observed that this is a PN code sequence corresponding to the original higher rate sequence at 16 in the Figure. As can be seen from Figure 2, the recovered sequence has an inherent delay relative to the original higher rate sequence of three chips of the original higher rate sequence. This inherent delay will be in addition to the delay corresponding to the propagation time from transmitter to receiver, and it can be calculated for any high rate sequence from which the low rate sequencies are derived.

Reverting to Figure 3, the recovered high rate sequence is supplied from the multiplication circuit 44 to a range meter 46 in which it is correlated with a locally generated corresponding high rate sequence so as to generate a time signal which is accurately dependent on the propagation time of the radio signals from the transmitter to the receiver.

In an operative radio positioning system, there will, as mentioned above, be at least three transmitters such as shown in Figure 1 at different geographical locations and the receiver of Figure 3 will be required to receive the sets of radio signals from each of the three transmitters, as well as any further transmitters within range. Thus, the receiver of Figure 3 will be adapted to tune successively to the predetermined carrier frequencies from each of the transmitters providing radio positioning coverage, and to generate therefrom appropriate time signals. In order to determine the position of the receiver, these time delay signals are compared relative to each other to identify LOPs, and the receivers position.

In such a system each transmitter may use a different set of carrier frequencies or all the transmitters may use the same set of carrier frequencies with allocated time slots (time doman multiple access

TDMA).

Referring now to Figure 4, one advantage of the above described radio positioning system embodying the present invention is illustrated where different carrier frequencies are used. In Figure 4, the upper graph illustrates the frequency spectrum of a high rate PN code phase modulated on a carrier frequency F. The band width of the modulated carrier to the first null points on either side of the central carrier frequency is $2f_c$, where f_c is the chip rate of the PN code sequence. In practice, for a PN code modulated carrier, the spectrum is not continuous but comprises a set of lines as shown in the drawing spaced by the rate of repetition of the PN code sequence as a whole, i.e. f_c/L where L is the number of chips in a code sequence before repeating. The example in Figure 4 illustrates a fifteen chip sequence.

For radio positioning systems using PN code spread-spectrum techniques, the chip rate of a single PN coded transmission should be sufficient to permit the required range resolution at the receiver. Obtaining a range resolution of plus or minus 10 metres, with a timing resolution within the duration of a single chip of 0.01, implies a chip rate of say 300 kHz. In order to give an unambiguous range for the radio positioning system of say 1,000 kilometre, the minimum sequence length for the PN coded single signal should be 2,047. This figure assumes that a maximal length PN code is employed generated by feedback connected shift registers in the usual way.

Thus, reverting to the upper graph in Figure 4, the band width for a single carrier signal phase modulated with a PN code having a chip rate of 300 kHz is 600 kHz. There may be substantial difficulties in finding a gap of 600 kHz within the available radio frequency sprectrum to locate not only one but a number of transmitters having different central frequencies and each with signal band

widths of 600 kHz.

By splitting the single high rate PN code illustrated in the upper graph of Figure 4, into a number, say 4, lower rate codes, efficient utilisation of the available band width can be maximised. In the example as illustrated in Figures 1 and 3, the single high rate code is sampled and split into four codes each having one quarter of the higher chip rate. Thus in the above described example where the band width of a single modulated signal would be 600 kHz, the band width of each of four carriers modulated with lower rate codes is 150 kHz. As shown in the lower graph of Figure 4, one of the four lower rate encoded carrier signals may be retained with the central carrier frequency F of the wide band signal shown in the upper graph. The other three carriers are distributed elsewhere in the frequency spectrum with central carrier frequencies F_1, F_2 and F_3. The frequencies F, F_1, F_2 and F_3 are selected to make use of available gaps in the frequency spectrum so as to minimise interference with other spectrum users. At the receiver, all four signals are received, the lower rate codes recovered and from these lower rate codes a higher rate code is re-established, having all the original timing information. Thus the higher rate code may still be used to obtain the originally required range resolution.

Although the examples of Figures 1 and 3 and as illustrated in Figure 4 contemplate only dividing the original higher rate PN code into four lower rate codes each having one quarter the original chip rate, the invention may of course be used to divide the original code into many more lower rate codes of further reduced chip rate as long as the code division is relatively prime to the higher rate sequence, and the minimum chip rate is greater than that required to discriminate a multipath sky

wave signal. This enables each individual modulated carrier signal to be relatively narrow band and to be located in correspondingly small available gaps in the spectrum.

Figures 5 and 6 illustrate conventional methods of Spread-Spectrum signal acquisition and tracking. In Figure 5, an incoming signal from antenna 50 is first amplified in rf amplifier 51 before passing through a band pass filter 52. A locally generated reference PN code is produced by generator 53. The locally generated code at this stage is at the lower chip rate of each individual received radio frequency signal. The locally generated code from the generator 53 is modulated on a local oscillator signal at a frequency $f_0 + f_1$, where f_0 is the carrier frequency of the received radio signal. The modulated local oscillator signal is then mixed in a mixer 54 with the received radio signal and the resulting difference frequency signal is filtered in a second band pass filter 55 before detection in an envelope detector 56 before supply to an integrate and dump circuit 57 a dismiss threshold circuit 58 and a search control circuit 59 which in turn controls the timing of the reference PN code generator 53. The operation of the elements illustrated in Figure 5 bring the generator 53 so that the locally generated PN code is synchronised within plus or minus one chip with the PN code detected from the received radio signal.

Once the received code is acquired by the circuit of Figure 5, fine synchronisation with the received PN code is provided by the conventional signal tracking loop illustrated in Figure 6. In the top right hand corner of Figure 6 is illustrated a carrier tracking loop which enables the central carrier frequency of the received signal to be tracked over Doppler shifts corresponding to movement between transmitter and receiver. The lower part

of Figure 6 illustrates a PN code tracking loop known as a Delay-Lock-Loop. The local oscillators LO_1 and LO_2 are modulated by two PN reference sequences displaced in time by an amount less than one code chip. After mixing with the received signal and band pass filtering, the mixed signal is further mixed with the output of the carrier tracking loop, and the two mix signals, from the two time displaced PN reference sequences, are supplied to a different circuit and the result used to control the output frequency of a voltage controlled oscillator (VCO) which clocks the reference PN code generator. The output of this reference PN code generator constitutes the output of the respective receiver channel.

The output PN codes from the various receiver channels are multiplied together as described above to recover a high rate reference signal which is itself then correlated with a reference high rate signal to provide acute time resolution for the received signal.

Figure 7, illustrates the correlation coefficient of the receiver for the time difference between reference and received PN code signals. The time axis in Figure 7 is measured in units of lower rate code chip. In order to clearly discriminate between the direct signal from the transmitter and a multipath sky wave signal arriving after a delay of τ_d, it can be seen that this time delay must be longer than two chips, implying a minimum chip rate for the lower rate signals of $2/\tau_d$. The minimum sky wave delay likely to be experienced is about 70μS so that the lower rate chip rate should be significantly greater than 30 kHz.

Mathematical analysis and computer simulation of the described split signal system of spread-sprectrum radio positioning has demonstrated that under certain conditions for the same effective power at the receiver, the multiple relatively narrow band signals from a

transmitter provide substantially the same range resolution as a single wide band signal. Figure 8 is a block diagram of a computer simulation of the split signal system described above, making use of a communications simulation software package known as COMDISCO from Comdisco Systems Inc. This provides computer aided engineering tools and a digital signal processing building-block library. The software can be used to develop and simulate digital signal processing algorithms and to evaluate various architectural approaches to a design.

Looking at Figure 8, a high rate PN sequence at 60 is sampled at 61 to provide four low rate signals. Noise is added to each of these signals at 62, 63, 64 and 65 and they are then subjected to controllable delays at 66 to 69 and then supplied to tracking loops 70 to 73. The outputs of the tracking loops are multiplied together and then correlated at 74 with the output of the original high rate sequence and the result supplied for statistical analysis at 75.

The simulations performed confirmed that the correlation of the recovered high rate signal and resulting time delay analysis closely followed that predicted by theory.

Considering Figure 9, this illustrates graphically the predicted rms range uncertainty in metres for a split signal system employing four carriers each modulated with PN code sequences at 75 kHz chip rate, with corresponding wide band spread-spectrum signal with a chip rate of 300 kHz. The difference in range uncertainty of 12 metres is due to the additional code self noise on the split signals, which is $k^{3/2}$ times that for the wide band signal, where $k = 4$ in this example. In fact when the receivers of each system are locked and tracking, code noise can be neglected so that the performances of the two

systems are identical.

Figure 9 also illustrates the characteristics of existing known radio positioning systems which use similar wide band signals. The Spot navigation system is similar to a single one of the split signal carrier frequencies, since the chip rate of Spot is close to 75 kHz. Geoloc uses a wide band DS-SS signal of $2^{23}-1$ chips at a chip rate 666 kHz. Thus a Geoloc like signal is broadly equivalent to an eight channel split signal embodying the present invention where each split signal has a chip rate of about 75 kHz. Figure 10 compares the range uncertainties of a Geoloc like signal with eight Spot-like signals each of 75 kHz embodying the present invention. The curves confirm the similarity of performance as predicted and the discrepancy illustrated tends to the self noise limit of 12 metres.

In practice, when thermal noise is dominant in the receiver, a split signal system can achieve the same performance as a conventional wide band system.

One advantage of the split signal system described is that it enables relatively narrow gaps in the radio frequency spectrum to be used flexibly, whilst retaining the attributes of wide band SS systems.

Because the signals from a single transmitter can comprise a number of carrier frequencies travelling over the same propagation path, channel differential delays between the different carriers could be measured at the receiver, these delays arising due to frequency dependent propagation effects. Such delays could then be used for correction purposes in the radio positioning process. It will be appreciated that the signals from different transmitters can also be at different carrier frequencies and might suffer from such differential delays. The receiver could use estimates of such delays derived from the signals from any one transmitter for correcting for

frequency dependent differential delays in the signals from different transmitters. In order to achieve a range resolution of better than ± 10 metres, the PN code itself might be employed to provide only a relatively coarse range measurement and to use measurements of carrier phase for fine resolution. The presence of multiple carriers in a split signal system from the same transmitter permits the phase differences between carriers to be measured in a manner corresponding to the Omega or Hyper-Fix navigation systems, as well as measuring the phases of single carriers.

Further, the relatively narrow band of each individual carrier in the split signal technique should minimise the effects of differential phase distortion due to propagation over inhomogeneous media. In wide band spread-spectrum techniques, when the fractional band width exceeds 10% of the carrier, complex phase-group delay compensation circuits are needed in the receiver.

As mentioned, the split signal technique illustrated above enables multiple narrow band signals to be transmitted from each transmitter instead of a single wide band single. These narrow band signals can be located in available gaps in the radio frequency spectrum and can utilise such gaps which are available only for a limited time. Techniques may be employed at the receiver for searching for the various carrier frequencies in operation from each transmitter. With the above described technique in which a single high rate PN code is sampled at the transmitter to create the lower rate codes, the code sequence in each of the lower rate codes is identical, though at the lower rate, to the original sequence of the higher rate code. This is convenient for identifying the signals from each transmitter.

Where signal identification is not a problem, the multiple lower rate codes generated at each transmitter

could be different code sequences having the same overall code length and a common chip rate.

The preceding description has concentrated on an application of the invention involving radio positioning. The invention may also be applicable to other techniques where the propagation time of radio signals is used for ranging or positioning purposes. For example in radar techniques, multiple carriers could be transmitted each encoded with lower rate signals for reflection by a target and reception back at the transmitting position. The regenerated high rate code signal could then be used for accurate ranging. The use of multiple transmitted carrier frequencies could be an advantage in providing immunity to jamming and other counter measures.

CLAIMS

1. Radio frequency ranging apparatus comprising a transmitter having a pseudorandom noise (PN) code generator and a modulator to modulate a carrier frequency with the generated PN code for transmission; and a receiver comprising a processing means incorporating a correlator to correlate a PN code, recovered from a radio signal received from the transmitter, with a similar reference PN code and providing a time signal dependent on a propagation time for said radio signal between the transmitter and the receiver, wherein said PN code generator is arranged to generate a plurality of PN codes having the same number of chips and a common chip rate, said PN codes being equally time shifted one from the next within the period of a single chip of said PN codes, and said modulator is arranged to modulate a corresponding plurality of carrier signals with respective said codes for transmission as respective radio signals, and wherein the receiver is arranged to receive said respective radio signals and said processing means includes combining means to combine the received PN codes to recover a higher rate PN code having a chip rate which is the product of said common chip rate and the number of said received PN codes, said correlator being arranged to correlate said recovered higher rate PN code with a similar reference PN code.

2. Radio frequency ranging apparatus as claimed in Claim 1, wherein said PN code generator in the transmitter comprises means to generate a PN code having a higher chip rate and sampling means to sample the chips of said higher rate PN code sequentially to form said plurality of PN codes at a common lower chip rate which is equal to said

higher rate divided by the number of said plurality of PN codes.

3. Radio frequency ranging apparatus as claimed in Claim 1 or Claim 2 wherein said modulator is arranged to modulate a corresponding plurality of carrier signals each having a different frequency, such that the band widths of each carrier signal does not substantially overlap.

4. Radio frequency ranging apparatus as claimed in Claim 1 or Claim 2 wherein said modulator is arranged to modulate a corresponding plurality of carrier signals each having substantially the same frequency.

5. Radio frequency ranging apparatus as claimed in Claim 1 or Claim 2 wherein said modulator is arranged to modulate a corresponding plurality of carrier signals, each having a different frequency such that the band widths of each carrier signal substantially overlap.

6. Radio frequency ranging apparatus as claimed in any preceding Claim, wherein said combining means comprises adding means for performing modulo two addition of the received PN codes.

7. Radio frequency ranging apparatus as claimed in Claim 6 wherein the chips of the PN codes are represented as +1 and -1 in accordance with their binary state, and the combining means comprises multiplying means to multiply together the chips of the received PN codes.

8. Radio frequency ranging apparatus as claimed in any preceding claim and configured as radio positioning apparatus, wherein the apparatus includes at least three

said transmitters and at least one said receiver, said processing means thereof providing said time signals for each of the transmitters from which radio signals are received at the receiver and identifying a position for the receiver relative to the transmitters from said time signals.

9. Radio frequency ranging apparatus as claimed in Claim 8, wherein each said transmitter has different sets of carrier frequencies.

10. Radio frequency ranging apparatus as claimed in Claim 8, wherein each said transmitter has the same set of carrier frequencies and transmits for a predetermined time period on the set of carrier frequencies.

11. A receiver for use in radio frequency ranging apparatus as claimed in any preceding claim wherein the receiver comprises processing means incorporating a correlator to correlate a received radio signal modulated with a PN code with a similar reference PN code and providing a time signal dependent on a progagation time for said radio signal between a transmitter and the receiver, wherein the receiver is arranged to receive a plurality of radio signals from a transmitter comprising respective carrier signals modulated by respective PN codes each having the same number of chips and a common chip rate, said PN codes being equally offset in time one from the next within the period of a single chip of said PN codes, and the processing means includes combining means to combine the received PN codes to recover a higher rate PN code having a chip rate which is the product of said common chip rate and the number of said received PN codes, said correlator being arranged to correlate said

recovered higher rate PN code with a similar reference PN code.

12. A receiver as claimed in Claim 11, wherein said receiver is arranged to receive a plurality of radio signals comprising a plurality of carrier signals each having a different frequency, the band widths of each carrier signal not substantially overlapping.

13. A receiver as claimed in Claim 11, wherein said receiver is arranged to receive a plurality of radio signals comprising a plurality of carrier signals each having substantially the same frequency.

14. A receiver as claimed in Claim 11, wherein said receiver is arranged to receive a plurality of radio signals comprising a plurality of carrier signals each having a different frequency the band widths of each carrier signal substantially overlapping.

15. A transmitter for use in radio frequency ranging apparatus as claimed in any preceding claim wherein the transmitter comprises a pseudorandom noise (PN) code generator and a modulator to modulate a carrier frequency with the generated PN code for transmission, wherein said PN code generator is arranged to generate a plurality of PN codes having the same number of chips and a common chip rate, said PN codes being equally offset in time one from the next within the period of a single chip of said PN codes, and said modulator is arranged to modulate a corresponding plurality of carrier signals with respective said codes for transmission as respective radio signals.

16. A transmitter as claimed in Claim 15 wherein said modulator is arranged to modulate a corresponding plurality of carrier signals each having a different frequency, such that the band widths of each carrier signal does not substantially overlap.

17. A transmitter as claimed in Claim 15, wherein said modulator is arranged to modulate a corresponding plurality of carrier signals each having substantially the same frequency.

18. A transmitter as claimed in Claim 15, wherein said modulator is arranged to modulate a corresponding plurality of carrier signals each having a different frequency, such that the band width of each carrier signal substantially overlaps.

19. Radio frequency ranging apparatus substantially as hereinbefore described with reference to and as illustrated in the accompanying drawings.

20. Radio positioning apparatus substantially as hereinbefore described with reference to and as illustrated in the accompanying drawings.

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Examiner's report to the Comptroller under S: :ion 17 (The Search Report)

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(i) UK Cl (Edition L) H4D (DPDA, DPDD, DPDX, DPBC, DPBX, DPX, DSX, DRPM, DRPN, DRPP, DRPQ, DRPR, DRPS)

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Databases (see over)

(i) UK Patent Office

(ii)

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Documents considered relevant following a search in respect of claims ALL

Category (see over)	Identity of document and relevant passages	Relevant to claim(s)
A E	GB 2259820 A (GEC AVIONICS) nb. page 6 line 16 to page 7 line 2	
A	EP 0362992 A2 (NKK CORP) eg abstract	

SF2(p) 1WL - doc99\fil000701

Category	Identity of document and relevant passages	Relevant to claim(s)

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